AN INVESTIGATION OF JET THROTTLING CHARACTERISTICS IN AN INCOMPRESSIBLE FLOW

by

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United States
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THESIS

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ABSTRACT

The effect of injecting an incompressible (water) jet into a crossing mainstream water flow is investigated experimentally. The results are presented in terms of the reduction in mainstream flow rate (throttling) as a function of jet flow rate and angle of injection. The data are compared with a control volume analysis in which the two streams are assumed to mix prior to exiting the control volume.

Although the jet proved less effective than predicted as a throttling device, qualitative trends were verified. Changing the injection angle from 90° to 120° improved throttling by 25%. Smoothing the orifice to a nozzle increased throttling, but not as drastically as a 10° angle change. System refinement and a greater variation of jet parameters are necessary, however, before conclusions can be made as to the value of incompressible throttling.

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NOMENCLATURE

A	flow area
B	height of mainstream duct
b	width of jet
E	internal energy/lbm of mainstream
h_L	head loss
K	mixing loss coefficient
k	head loss coefficient
M_L	mixing loss
P	mainstream pressure
Q_o	reference flow rate
Q	mainstream flow rate
q	jet flow rate
U	mainstream velocity
u	jet velocity
w	channel depth
α_1	injection angle
ρ	density

SUBSCRIPTS

0	denotes reference condition (without jet injection)
1	denotes condition at upstream control volume station
2	denotes condition at downstream control volume station
a	denotes ambient condition
e	denotes pipe exit condition
T	denotes stagnation condition

SUPERSCRIPTS

$\bar{f}$ f/B

ACKNOWLEDGMENT

The author would like to take this opportunity to express his thanks to Doctor Robert H. Nunn for his counsel and guidance during the course of this investigation. A special note of appreciation is also given to Mr. Joseph Beck of the Mechanical Engineering Shop for his patience and efforts in the construction of the experimental apparatus.

I. INTRODUCTION AND BACKGROUND

The purpose of this thesis was to conduct an experimental investigation into the flow reduction characteristics of a two-dimensional, incompressible jet issuing into a confined, incompressible cross-flow.

As classically stated, the jet problem considers the impingement of a round jet on a cross-flow of infinite extent [8,9,17]. However, this differs considerably from the problem under discussion. Unlike the case for an infinite mainstream, a confined flow cannot be displaced to make room for the jet without an accompanying decrease in primary (mainstream) flow rate as well as acceleration of the primary stream and the establishment of steep pressure gradients in the flow field. The use of a two-dimensional jet (a slot extending across the floor of the test section) rather than the more common three-dimensional (round) type eliminates the possibility of primary flow being diverted around the sides of the secondary (jet) stream. The two-dimensional slot increased mainstream displacement for a given jet flow. These modifications to the statement of the classical problem make a great deal of the literature inapplicable to this thesis.

The applicable literature includes studies by Martin [11], McArdle [12], and Nunn [13]. They have studied both experimentally and analytically the problem of the jet-mainstream interaction for the compressible case and have found it to be an effective means of controlling the rate of mainstream flow. In such a situation, the sum of the primary and secondary flow rates will be less than that of the unimpeded mainstream. This form of "fluidic" control is termed aerodynamic throttling.

If the incompressible case proves as effective as compressible throttling, then it might be found that in certain situations a jet would be superior to a mechanical throttling valve. The jet would have the advantage of no moving parts and erosion and corrosion problem would be alleviated. There are, however, no data available for the incompressible case to confirm or refute the value of the "fluid valve." Experimentation has constituted the main effort of this study; mass flow rate for various inlet geometries and angles of injection has been the main dependent variable.

Although priority was given to obtaining physical evidence of throttling, some attempt at analysis was made in order to identify the dominant parameters of the problem. Two types of flow interaction were considered. The first type assumes that both streams remain as separate entities and never mix. The other assumes that the streams mix immediately upon jet entry. These are the extreme cases. The true situation is expected to lie between the two. For purposes of analysis, however, they are considered as being independent and are discussed in more detail in section II.

II. ANALYTICAL MODEL

In order to facilitate the formulation of an analytical model, one of two types of interaction is usually hypothesized. The first, called the vortex sheet hypothesis, considers the jet and mainstream as separate entities. They maintain separate identities and their interface is a line of velocity discontinuity. The second, referred to as the mixing hypothesis, is based on the premise that in a given distance, the jet and mainstream have mixed to the extent that they form one uniform stream. It is incorrect to postulate that the two cases are not combined in any given flow situation, but for ease of analysis this independence will be assumed. Since vortex sheet models have already been developed by Martin [11] and Nunn [13], only the mixing hypothesis will be considered in detail in this section.

Mixing is considered to begin at the point of jet injection and the two streams become one in a short distance. This mixing region is bounded upstream near the point of jet injection (station 1), downstream by an imaginary plane where the two flows have combined to form one uniform stream (station 2) and on four sides by the walls of the test section. This region is referred to as the control volume (see Fig. 1(c)).

Because of the length of pipe used upstream of the test section, it is assumed that the mainstream is a uniform, fully-developed turbulent flow upon entering the control volume. It is further assumed that after the two streams have mixed, that is at station 2, the flow is once again uniform.

The interaction of the two streams is complex enough so that to obtain a mathematical model to describe the turbulent mixing would be beyond the scope of this thesis. To avoid describing the interaction, control volume methods are used and the governing equations of the flow field are written for stations 1 and 2. Evaluation of flow properties at these positions provides evidence of jet interaction without requiring a description of the mechanism of mixing. It is on this basis that the momentum, continuity and energy equations will be written and manipulated to yield normalized flow rate expressions based on a gross mixing loss.

A. MIXING HYPOTHESIS

The flow rates per unit depth are defined as

$$Q_0 = U_{20}B$$
$$Q = U_1 B$$
$$q = u_1 b_1$$
$$Q + q = U_2 B.$$

The continuity equation for the control volume is

$$BU_1 + b_1 u_1 = BU_2 . \tag{1}$$

Neglecting gravity forces and noting that the stream is assumed to be completely mixed at station 2, the momentum equation for the control volume becomes

$$P_1 B + \rho U_1^2 B + \rho u_1^2 b_1 \cos\alpha_1 = P_2 B + \rho U_2^2 B \tag{2}$$

As assumed, the mechanism of turbulent mixing within the control volume can be described in terms of a gross mixing loss between stations 1 and 2. Defining this loss as the increase in internal energy per pound of mainstream flow, the energy equation for the control volume is

$$\frac{P_1}{\rho} + \frac{U_1^2}{2} = \frac{P_3}{\rho} + \frac{U_2^2}{2} + (E_T - E_1) = \frac{P_2}{\rho} + \frac{U_2^2}{2} + M_L \; . \tag{3}$$

At the pipe exit, the total pressure is

without the jet $\quad \frac{P_T}{\rho} = \frac{P_a}{\rho} + \frac{U_{eo}^2}{2} + h_{Lo}$,

with the jet $\quad \frac{P_T}{\rho} = \frac{P_a}{\rho} + \frac{U_e^2}{2} + h_L + M_L$;

hence $$M_L = \frac{U_{eo}^2 - U_e^2}{2} + h_{Lo} - h_L \; . \tag{4}$$

With the usual assumption that the head loss is proportional to the square of the velocity, it is assumed that

$$h_L = k \frac{U_e^2}{2} \text{ , and}$$

$$h_{Lo} = k \frac{U_{eo}^2}{2} \; .$$

Substituting these expressions into Eq. (4) gives

$$M_L = (1+k)\frac{U_{eo}^2 - U_e^2}{2} = K^2 \frac{U_{eo}^2 - U_e^2}{2} \; . \tag{5}$$

The energy equation between stations 2 and e can also be written as

without the jet $\quad \frac{P_{2o}}{\rho} + \frac{U_{2o}^2}{2} = \frac{P_a}{\rho} + \frac{U_{eo}^2}{2} + h_{Lo}$,

with the jet $\quad \frac{P_2}{\rho} + \frac{U_2^2}{2} = \frac{P_a}{\rho} + \frac{U_e^2}{2} + h_L$;

hence $$\frac{P_{2o} - P_2}{\rho} + \frac{U_{2o}^2 - U_2^2}{2} = \frac{U_{eo}^2 - U_e^2}{2} + h_{Lo} - h_L \; . \tag{6}$$

The right hand side of Eq. (6) is the previously derived form of the mixing loss (Eq. (4)). If variations in the pressure at station 2 are neglected, the equation becomes

$$M_L' = \frac{U_{2o}^2 - U_2^2}{2} \quad \text{(constant } P_2\text{)} \; . \tag{7}$$

Note that since $A_e U_e = B_w U_2$, the expression for constant P_2 corresponds to a value of K given by

$$K = \frac{A_e}{B_{w1}} \qquad \text{(constant } P_2\text{)}.$$

This expression provides a lower bound for the empirical evaluation of K.

Substituting $A_e U_{eo} = B_w U_{2o}$ into Eq. (5) and expressing the velocities in terms of flow rates gives

$$\frac{M_L}{\frac{1}{2}U_{2o}^2} = K^2 \left[1 - \left(\frac{Q+q}{Q_o}\right)^2\right]\left[\frac{B_w}{A_e}\right]^2 . \tag{8}$$

Writing a combined momentum-energy equation by subtracting Eq. (3) from (2) gives

$$M_L = \frac{U_2^2 - U_1^2}{2} - u_1^2 b_1 \cos\alpha_1 .$$

Dividing by $\frac{1}{2}U_{2o}^2$ and substituting flow rates yields

$$\frac{M_L}{\frac{1}{2}U_{2o}^2} = \left(\frac{Q+q}{Q_o}\right)^2 - \left(\frac{Q}{Q_o}\right)^2 - 2\left(\frac{q}{Q_o}\right)^2 \frac{\cos\alpha_1}{b_1} . \tag{9}$$

Equating (8) and (9) one obtains

$$\left[1 - \left(\frac{Q+q}{Q_o}\right)^2\right]\left[\frac{KB_w}{A_e}\right]^2 = \left(\frac{Q+q}{Q_o}\right)^2 - \left(\frac{Q}{Q_o}\right)^2 - 2\left(\frac{q}{Q_o}\right)^2 \frac{\cos\alpha_1}{b_1} .$$

Expanding the right hand side of the previous equation and completing the square, the solution becomes

$$\left[1 - \left(\frac{Q+q}{Q_o}\right)^2 - 2\left(\frac{Q+q}{Q_o}\right)\left(\frac{q}{Q_o}\right)\left(\frac{A_e}{KB_w}\right)^2 - \left(\frac{q}{Q_o}\right)^2\left(\frac{A_e}{KB_w}\right)^4\right]\left[\frac{KB_w}{A_e}\right]^2 =$$

$$\left[\frac{q}{Q_o}\right]^2\left[-1 - 2\frac{\cos\alpha_1}{b_1} - \left(\frac{A_e}{KB_w}\right)^2\right];$$

$$\frac{Q+q}{Q_o} = \sqrt{\left(\frac{q}{Q_o}\right)^2\left(\frac{A_e}{KB_w}\right)^2\left[1 + 2\frac{\cos\alpha_1}{b_1} + \left(\frac{A_e}{KB_w}\right)^2\right] + 1} - \frac{q}{Q_o}\left(\frac{A_e}{KB_w}\right)^2 . \tag{10}$$

The governing equations have now been combined in a form from which theoretical throttling curves can be plotted. However, knowledge of the physical constants of the system (the non-dimensional slot width, injection angle and the ratio of exit to downstream areas) and an estimate for K, the mixing loss coefficient, is required. The value of this mixing loss coefficient can be revised after compiling data and, by trial and error, a value can be assigned that provides the best correlation between theoretical and experimental curves.

B. VORTEX SHEET HYPOTHESIS

This model, derived by Nunn [13], requires knowledge of P_2 and its variations for solution. Since time was insufficient to study this aspect of the throttling problem and flow reduction evidence was the major goal of this thesis, only superficial pressure data were collected. Attempts at a solution using this limited amount of data were made but proved inconclusive.

III. EXPERIMENTAL EQUIPMENT AND PROCEDURE

The experimental apparatus consisted of a plexiglass test section, a dye injection system, a jet plenum chamber, and a backpressure regulating valve. In addition, a pressure gage, globe valve, pitot-static tube, orifice and corresponding mercury manometer banks were included for both the jet and mainstream lines. Figure 2 is a schematic diagram of the system and a photograph of the equipment is given in Figure 3.

The plexiglass test section was the component in which jet impingement occurred. The roof of the test section accommodated four flush wall taps to monitor the variation of pressure as the jet was injected. The floor was fitted with the two-dimensional jet slot. This part could be removed and replaced with a floor of different slot geometry or orientation. In this manner, the effect of varying the orifice area or injection angle could be studied with relative ease. The transparent sides permitted photography when dye injection was employed. The section was 12 inches long with a 2.115 x 2.080 inch cross section and was constructed of 1-inch thick plexiglass. Since plexiglass can sustain very little shear without cracking, it was required that the section be level and all other components be assembled so as to join with it to close tolerances.

The pressure gage, globe valve, pitot-static tube, orifice and manometers were present in each line to evaluate and control flow conditions. Since the experiment was to be conducted under conditions of constant mainstream total pressure, the globe valves were utilized to regulate the volumetric flow rates and control the total pressures of each stream. Volumetric flow rate was sensed by the orifices and total and static pressure recorded by the pitot-static tubes. The jet line, a 1-inch nominal diameter galvanized steel pipe, housed a "D+½D" type orifice with a throat diameter of .500 inches. The mainstream line, a 2-inch nominal diameter pipe of the same material, was metered by a flange tap orifice with a throat diameter of 1.470 inches. Calibration tests were run on both lines, verifying that the orifices conformed with ASME specifications. The pitot-static tubes in the primary and secondary lines were 1/8 and 1/16 inches, respectively. Due to the pressures and pressure drops involved, mercury was used as the manometer fluid. The pressure gages were installed to indicate the general range of readings to be expected and to provide a rough check on the other data collecting devices.

The dye injection system was a pitot tube inserted at a tee in the jet line. This was pointed downstream to reduce the head required for injection and compressed air was available to increase pressure in the dye chamber when the elevation head was insufficient. The dye, commercial bluing, was introduced approximately 18 inches upstream of the plenum chamber to provide the time and distance required for the dye to intermingle with the jet.

The plenum chamber served a threefold purpose. Firstly, being a 2-inch nominal diameter pipe, it served as a cover for the jet slot. Equipped with a gasket, the seal was watertight under all operating conditions. Secondly, it served as one of the vertical supports of the test section. Finally, the chamber was used for fluid collection and surge reduction. Since the jet line entered the plenum chamber from the side, velocity surges were dampened before reaching the test section. This caused the flow through the entry slot to be uniform and the jet to be approximately two-dimensional.

The last major component, the backpressure regulating valve, was added to increase the reliability of the system. If pressures were permitted to drop below atmospheric, the possibility of air entrainment in the manometer lines would be increased. To eliminate this problem, the backpressure valve was installed and adjusted to raise the overall system pressure to a level where all metered values were well above atmospheric pressure.

With the equipment assembled, both lines were fed by the same pump with flow rates regulated by globe valves.

The procedure for data collection was as follows:

1. Select a mainstream total pressure (without jet impingement) and maintain it by proper globe valve setting. The flow rate at this condition was the reference flow, Q_o.
2. Incrementally open the globe valve in the jet line.
3. Adjust the mainstream globe valve to restore the original primary total pressure.
4. Record the pressure drop across both orifices and the total pressure in each line.
5. Repeat steps 1 through 4 until the jet globe valve is fully open.
6. Repeat steps 1 through 5 for different total mainstream pressures.

In this manner, a family of throttling curves parametric in primary total pressure was plotted. For variations in slot geometry the same procedure was followed and data reduced in the same manner.

IV. EXPERIMENTAL STUDIES

A. OBSERVED PHENOMENA

Experimental data confirmed the ability of the incompressible side jet to decrease the flow rate of a crossing mainstream. When the angle of injection was 90 degrees, this reduction was so slight that the device was ineffective for flow control. Throttling increased as the jet was directed against the mainstream at greater angles, however, and when α had reached 120 degrees, the jet had enough influence on the primary flow to warrant its consideration as a fluid "valve." Figures 20(a) through (c) are photographs of the test section flow using flow visualization techniques as the angle of injection was varied.

An attempt at improving the effect of the normal, or perpendicular jet was made by shaping the sharp-edged orifice into a nozzle. (See Fig. 1(d)). It was hoped that this new geometry would provide greater jet penetration and, as a result, more throttling. In the lower ranges of secondary flow this was the case, but once again the effect of the normal jet was so slight that its use as a throttling device is doubtful. Figure 20(d) depicts normal entry through a nozzle while (e) shows nominally the same flow situation for a slot. It should be noted that jet penetration, as predicted, was greater for the nozzle.

The time and distance required for mixing was found to be a function of the relative magnitude of the total pressure of the two streams. For flow situations in which the total pressure of jet was much larger than that of the mainstream (i.e., $p_T \geq 5 P_T$), mixing was quite rapid as illustrated by Fig. 20(f). When the jet did not dominate the mainstream to such an extent, the two flows maintained their own identity longer as shown in Fig. 20(g). The fact that a large difference in pressure between the two streams caused rapid mixing is attributed, in part, to the requirement that the interface be a line of pressure continuity and the speed and severity of the transition to this condition at injection was governed by the size of the jet-mainstream pressure differential.

Since the rate of mixing varied with the relative pressure of the streams, it was impossible to define one downstream position as the location of station 2 for every case. In some cases the mixing appeared complete, while in others the stream was not uniform as it left the test section. Hence, downstream pressure data (needed to evaluate the vortex sheet hypothesis) would be subject to error unless care were taken to determine the position of station 2 for each case.

Finally, visual observation indicated that for all cases the jet shape changed abruptly as it passed from the jet slot into the mainstream. The jet increased in size in the longitudinal direction. This occurrence will be referred to henceforth as "spreading," and was visually verified during experimentation. The cause and effect of spreading will be discussed in the next section.

B. THE EFFECT OF A NON-UNIFORM MAINSTREAM VELOCITY

In the analysis of the theoretical model it was stated that the mainstream velocity was to be considered uniform upon entering the control volume. Since the velocity profile for a fully-developed turbulent flow is relatively flat, the assumption is valid over the entire test section with the exception of a small region near the wall. In this region, the mainstream velocity was small compared to the mid-channel value, and consequently the total pressure near the wall was lower. The jet, controlled experimentally, had a total pressure higher than the mainstream in every case. Noting that the total pressure discontinuity (implying a velocity discontinuity) along the jet-mainstream interface was a major cause of mixing of the two streams and this discontinuity was magnified in the region of non-uniform velocity, it may be expected that mixing would occur more rapidly near the wall. It was this accelerated, localized mixing that caused jet "spreading."

The effect of spreading can be illustrated by referring to the term representing the influx of jet momentum in the momentum equation ($L_1 u_1^2 \cos\alpha_1$) Rewritten, this becomes $q u_1 \cos\alpha_1$. Regardless of jet shape, the volumetric flow rate will remain constant, but an expanding jet causes a decrease in velocity. Thus the momentum influx of the secondary stream was decreased by spreading and the mainstream flow reduction due to jet injection was less. An empirical correction factor could be included in the analytical model to account for this phenomenon. Since the factor K was already present, none was added. However, the value of K will change accordingly as theory and experiment are compared.

It might be postulated that the non-uniform velocity profile also had an effect on the performance of the nozzle. The lack of a vena contracta caused the fluid issuing from the nozzle to have a lower velocity and total pressure than it would from a sharp-edged slot for the same flow rate. Again, a smaller pressure differential decreased spreading, which could account for the apparent increase in throttling above that recorded for the sharp-edged slot.

C. GRAPHICAL PRESENTATION OF DATA

The experimental and theoretical results of this thesis are presented in Figs. 4-19. All data were reduced with the aid of the IBM-360 computer and a smooth curve was fitted to the data.

Figure 4 is a plot of the data taken without jet injection and was used to determine the reference flow for each experimental situation.

Figures 5 through 12 show the effect of the side jet as the injection angle was increased. For each case there are two graphs. The first illustrates the effect of the jet on total flow rate; the second depicts the reduction in primary flow rate as the secondary flow rate is increased. In all these plots, theoretical results are superimposed on the data.

Figures 13 and 14 present the same type of data as the eight preceding graphs. For these cases, however, the shape of the jet duct is changed from a slot to a nozzle.

Figures 15 and 16 are summarizing plots of graphs 5-14. For these two curves, however, data points are omitted and smooth curves substituted for comparison purposes.

Figures 17-19 are theoretical throttling curves obtained from the mixing hypothesis. The first two figures indicate the sensitivity of the analytical model to variations in α_1 and K. The final plot is of theoretical throttling for that value of K which provides closest correlation between theory and experiment. A value of K=2.05, greater than the lower bound established by $Bw/A_e=1.67$, provides that fit.

An error analysis on the orifice flow rate equation resulted in an uncertainty ($\Delta Q/Q$) of approximately 1%. With few exceptions, the experimental scatter fell within this band of uncertainty.

The remaining figure, 20, is the photographic result of selected flow situations using dye injection.

V. CONCLUSIONS

1. The ability of the incompressible side jet to reduce effectively the flow rate of an incompressible mainstream is limited. Throttling improves as the angle of injection is increased or when the jet slot is replaced by a nozzle. Even in these cases, the amount of jet flow required to reduce the total output to 75% of its original value is large enough to restrict application of this device to situations where only moderate flow control is desired.

2. When the total pressure of the jet is much larger than the mainstream total pressure (i.e., $p_T \geq 5 P_T$), the two streams tend to mix rapidly. Since the mixing process is retarded when the total pressures are approximately equal, it is postulated that initial inequalities in jet and mainstream tend to promote mixing.

3. Near the wall the mainstream velocity (and hence total pressure) is lower than in the center stream. In the wall region, pressure differentials between jet and mainstream are exaggerated and for a short distance, rapid mixing occurs. This mixing reduces the momentum input of the jet and decreases throttling.

4. Inserting a constant into the analytical model to account for mixing loss permits the mixing hypothesis to be manipulated in such a way that theoretical results can be used to predict approximately the actual performance of the jet.

VI. RECOMMENDATION FOR FUTURE THESES

1. Continue to examine the effect on throttling of varying the geometry of the jet. That is to say, change the angle of injection, slot width, shape of the nozzle, or any combination of these.

2. Examine the effect of using a series of overlapping three-dimensional jets rather than one two-dimensional jet.

3. Repeat the experiment using two jets, one in the upper and lower plates of the test section. With this configuration it might be possible to approach the condition where the jet flow entirely eliminates mainstream flow.

4. Repeat the experiment using separate sources for the primary and secondary streams. In this manner, a greater range of flow rates could be obtained and control of the two streams would be greatly simplified.

5. Score a grid into the plexiglass wall of the test section. Using dye injection and precise photography, the exact shape of the jet would be determined. Knowing this, it would be possible to check the validity of some analytical analyses that predict jet shape. Examples are the classical hydrodynamic solution using free streamline theory or the analysis obtained from the vortex sheet theory.

6. Collect extensive pressure data in an effort to obtain an accurate prediction of throttling using the vortex sheet theory.

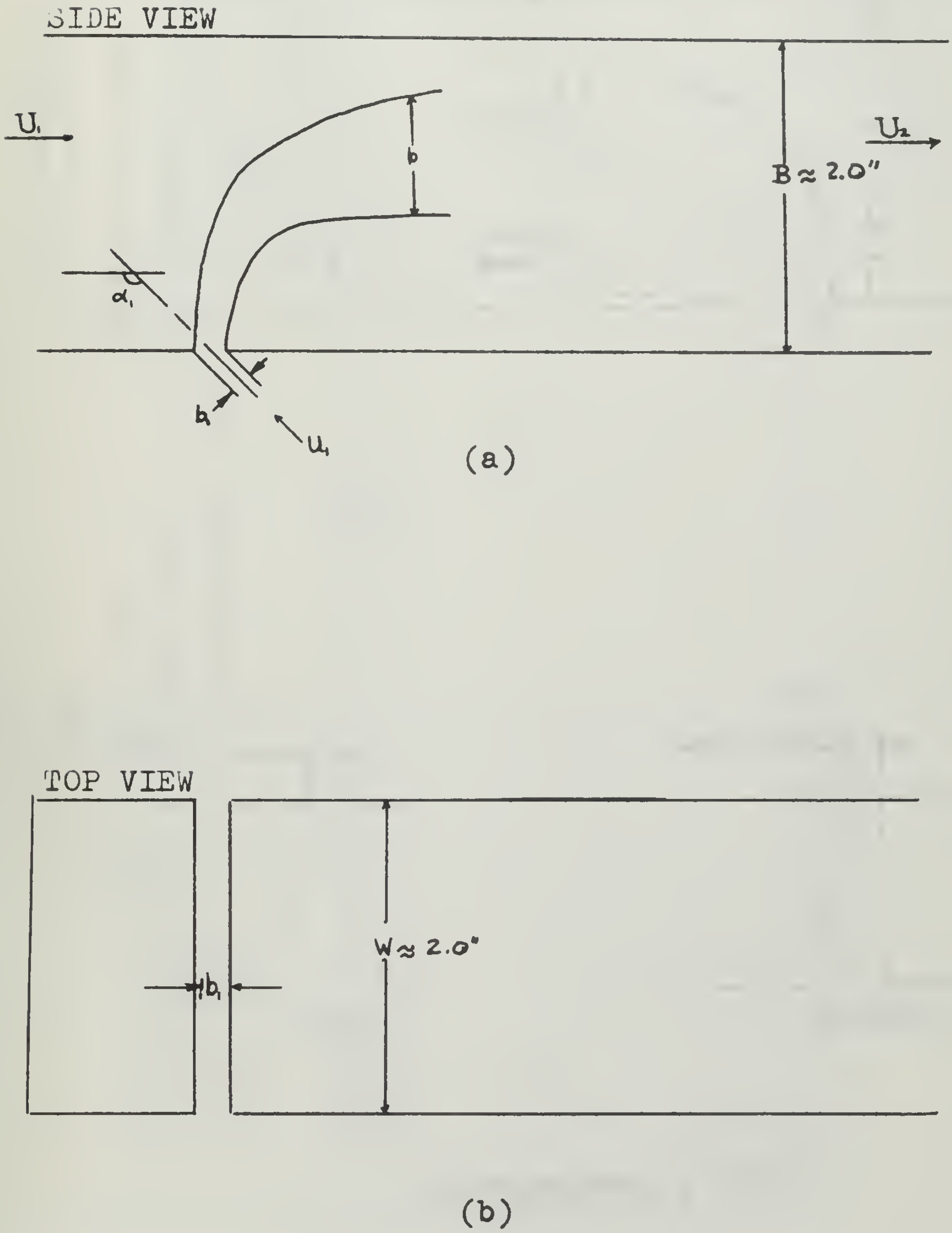
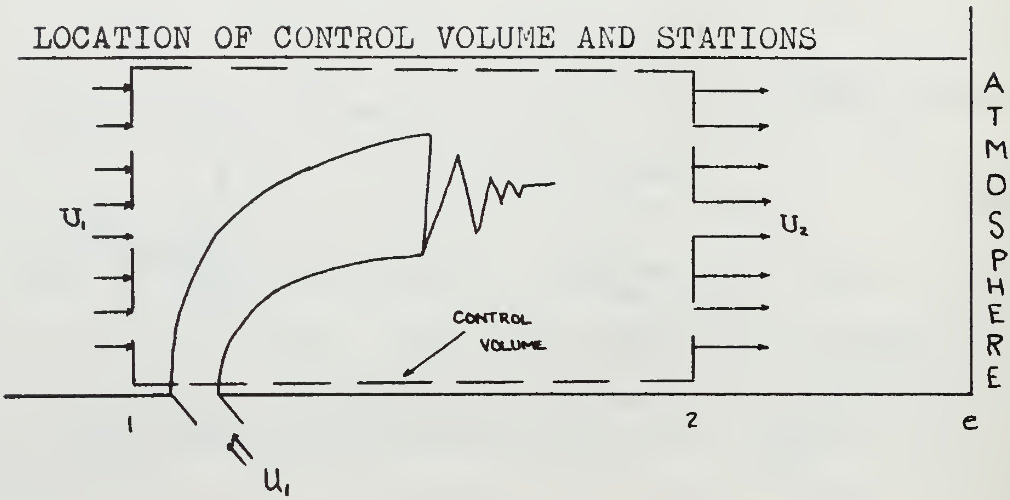
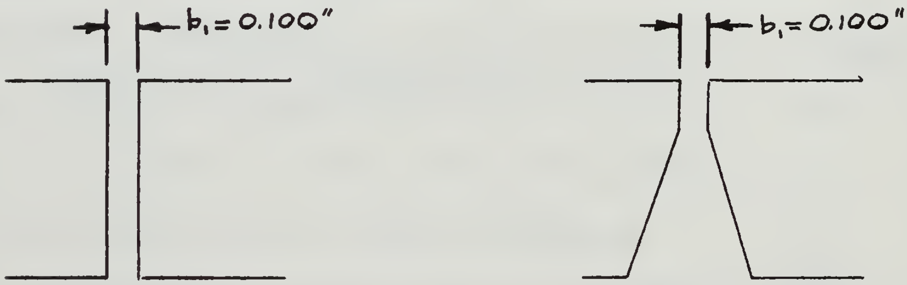


FIG. 1 NOMENCLATURE

LOCATION OF CONTROL VOLUME AND STATIONS



(c)



ORIFICE

NOZZLE

(d)

FIG. 1 NOMENCLATURE

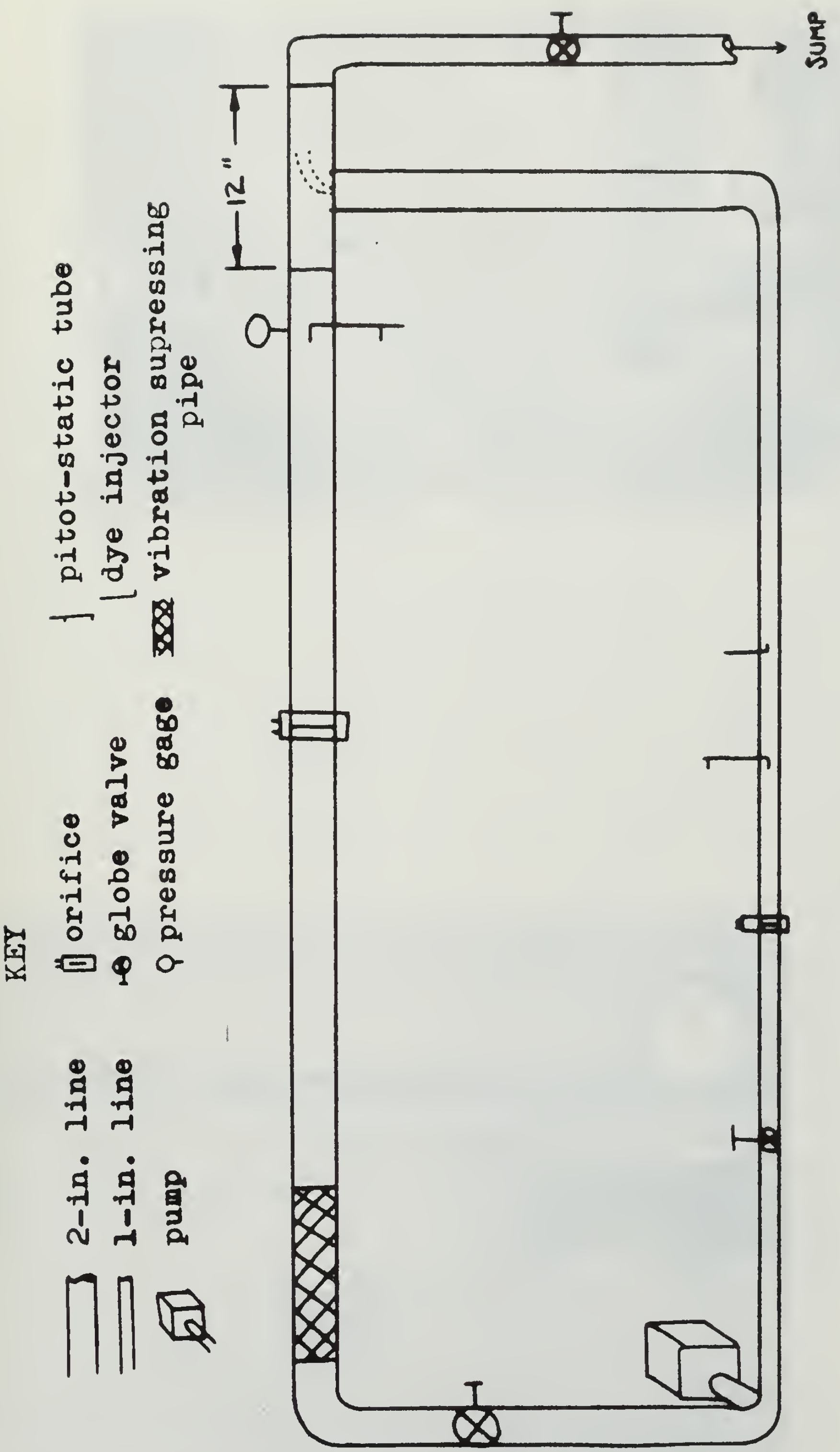
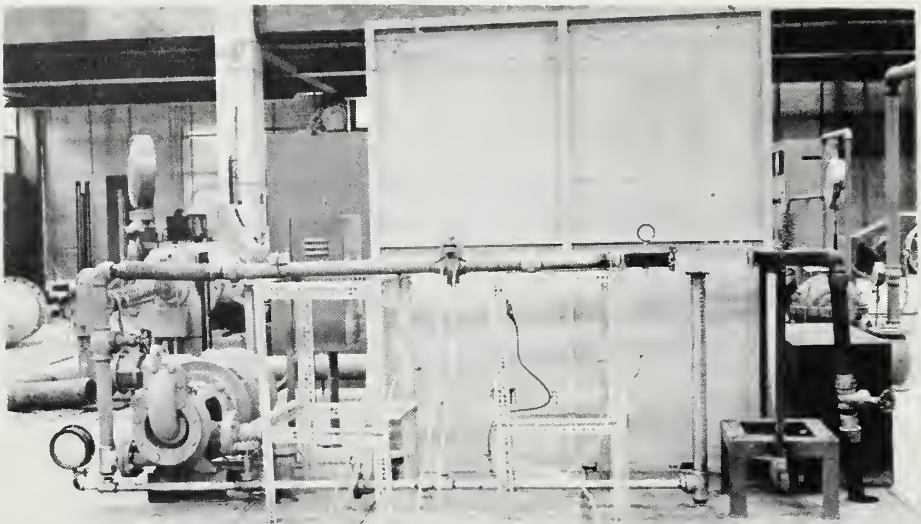


FIG. 2 SCHEMATIC DIAGRAM OF APPARATUS
(SIDE VIEW)



(a)

(b)

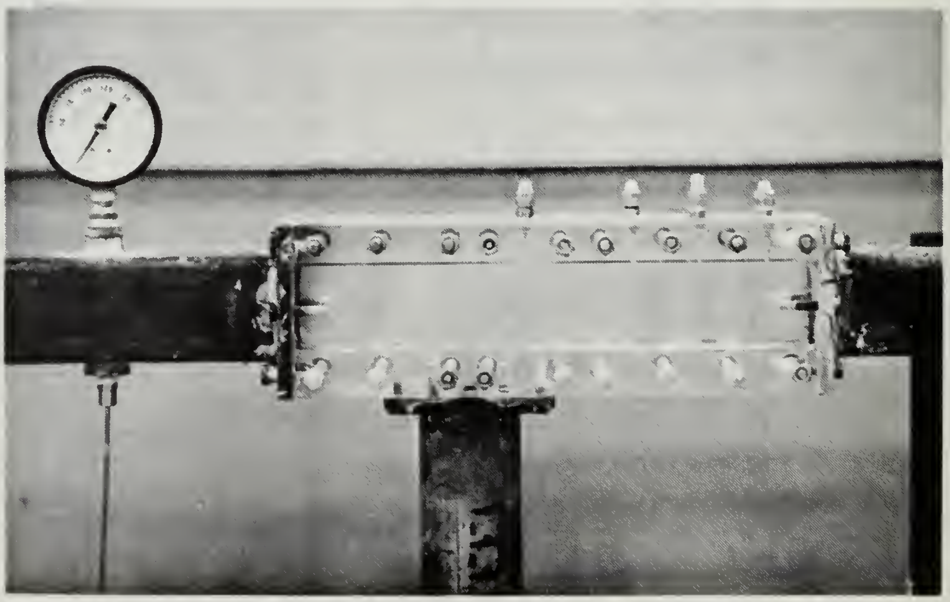


FIG. 9 [illegible]

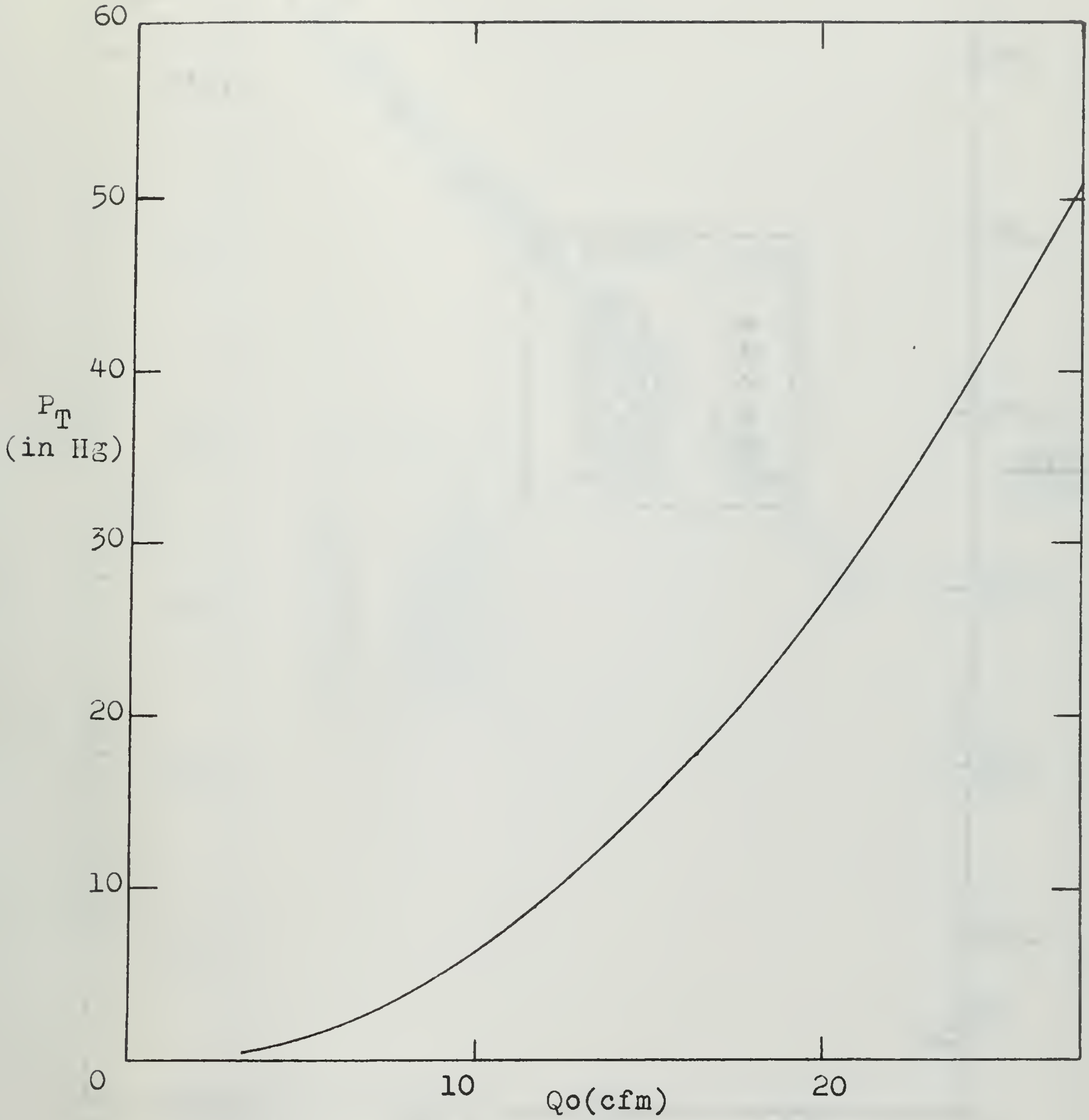


FIG. 4 REFERENCE FLOW CALIBRATION CURVE

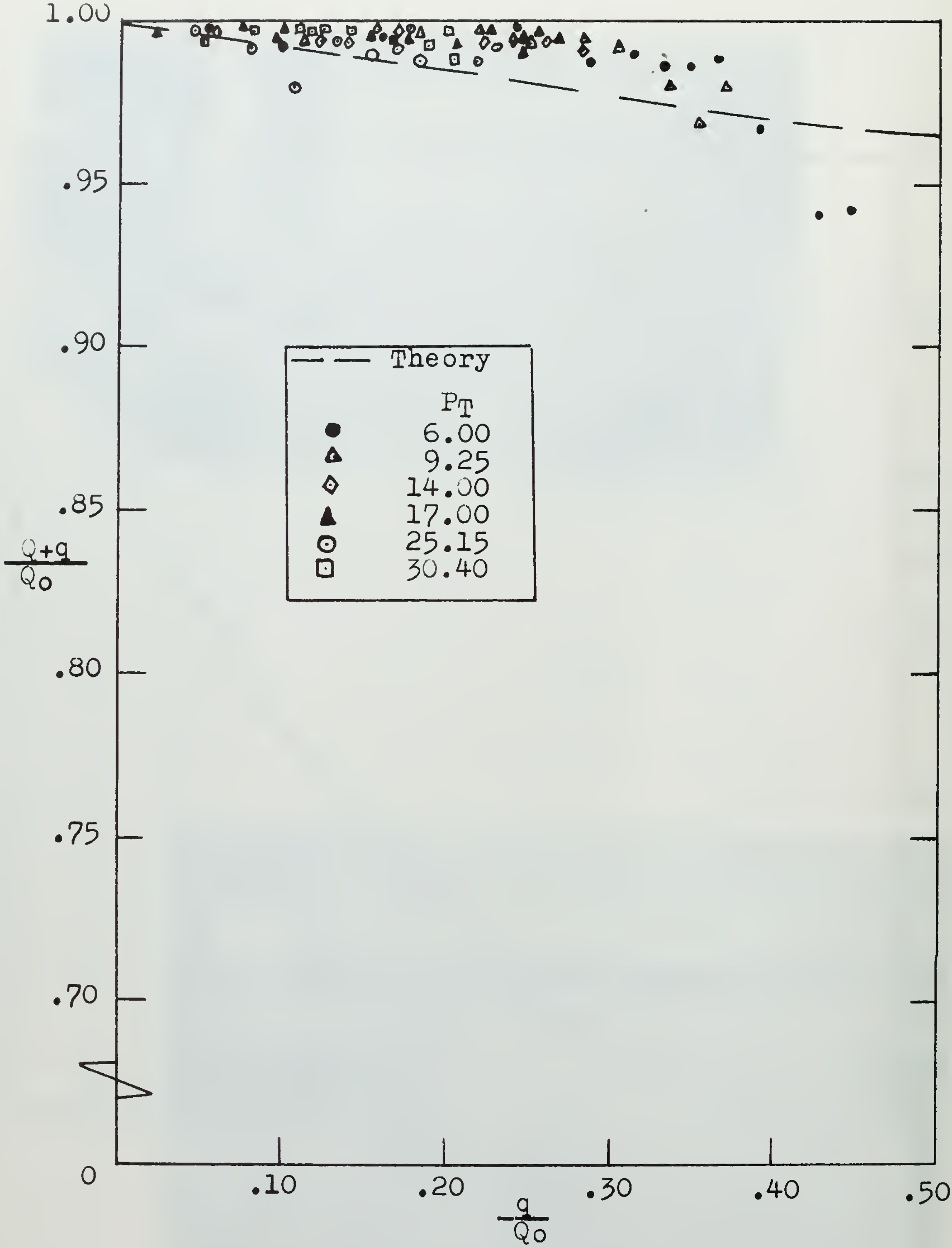


FIG. 5 EXPERIMENTAL THROTTLING DATA FOR A SHARP-EDGED ORIFICE (INJECTION ANGLE: 90 deg.)

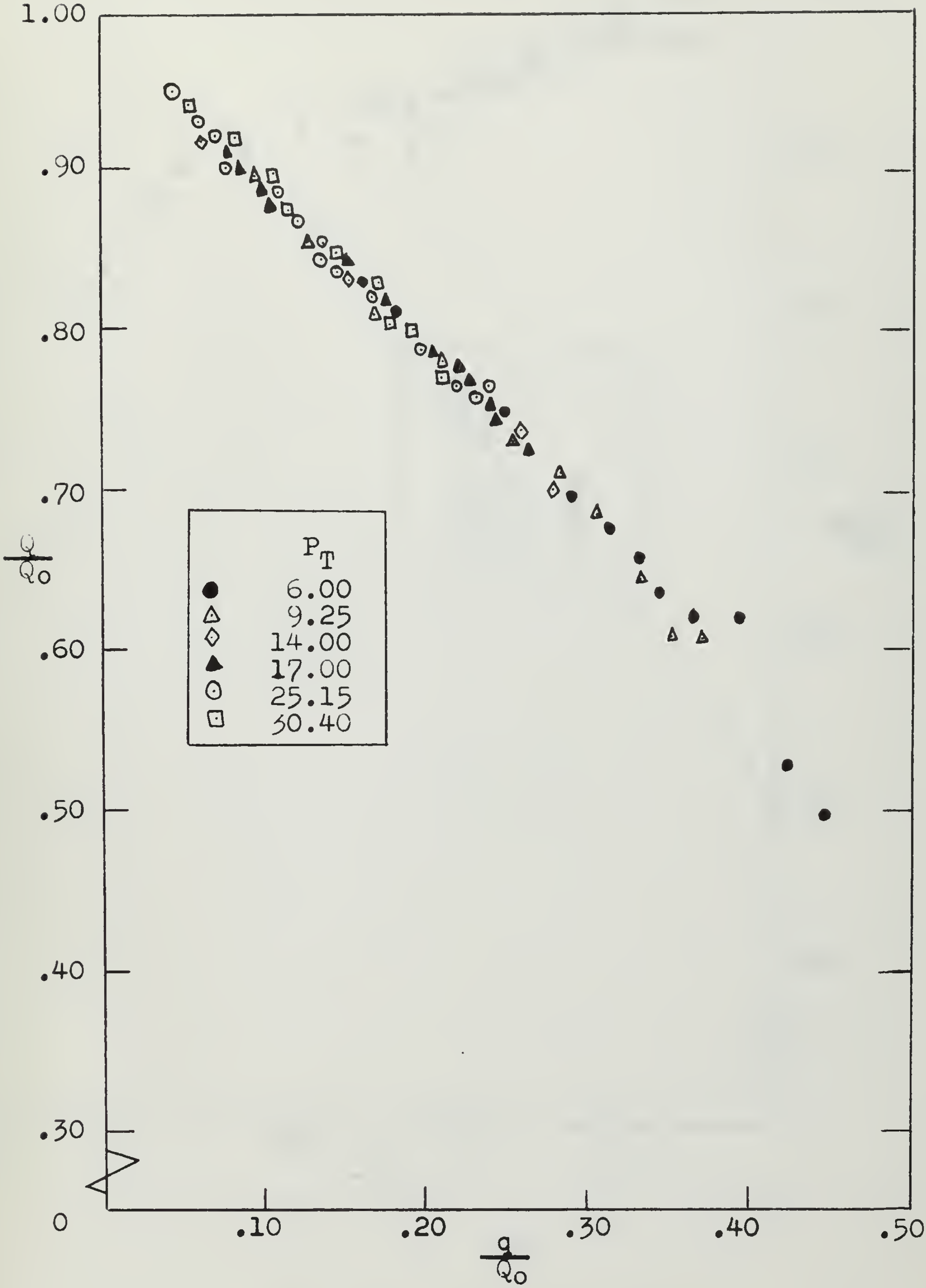


FIG. 6 PRIMARY-vs-SECONDARY FLOW RATES
FOR A SHARP-EDGED ORIFICE
(INJECTION ANGLE: 90 deg.)

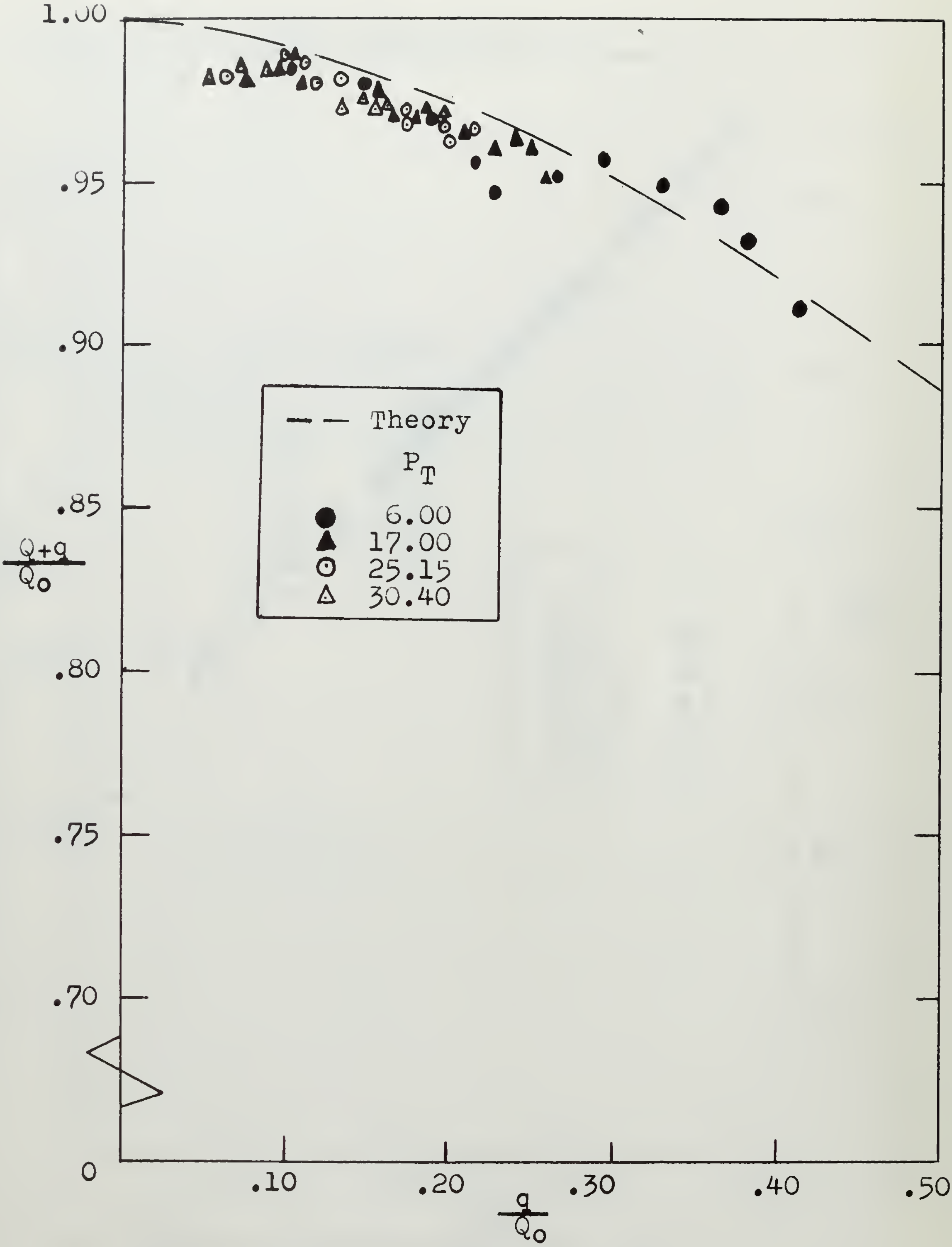


FIG. 7 EXPERIMENTAL THROTTLING DATA FOR A SHARP-EDGED ORIFICE
(INJECTION ANGLE: 100 deg.)

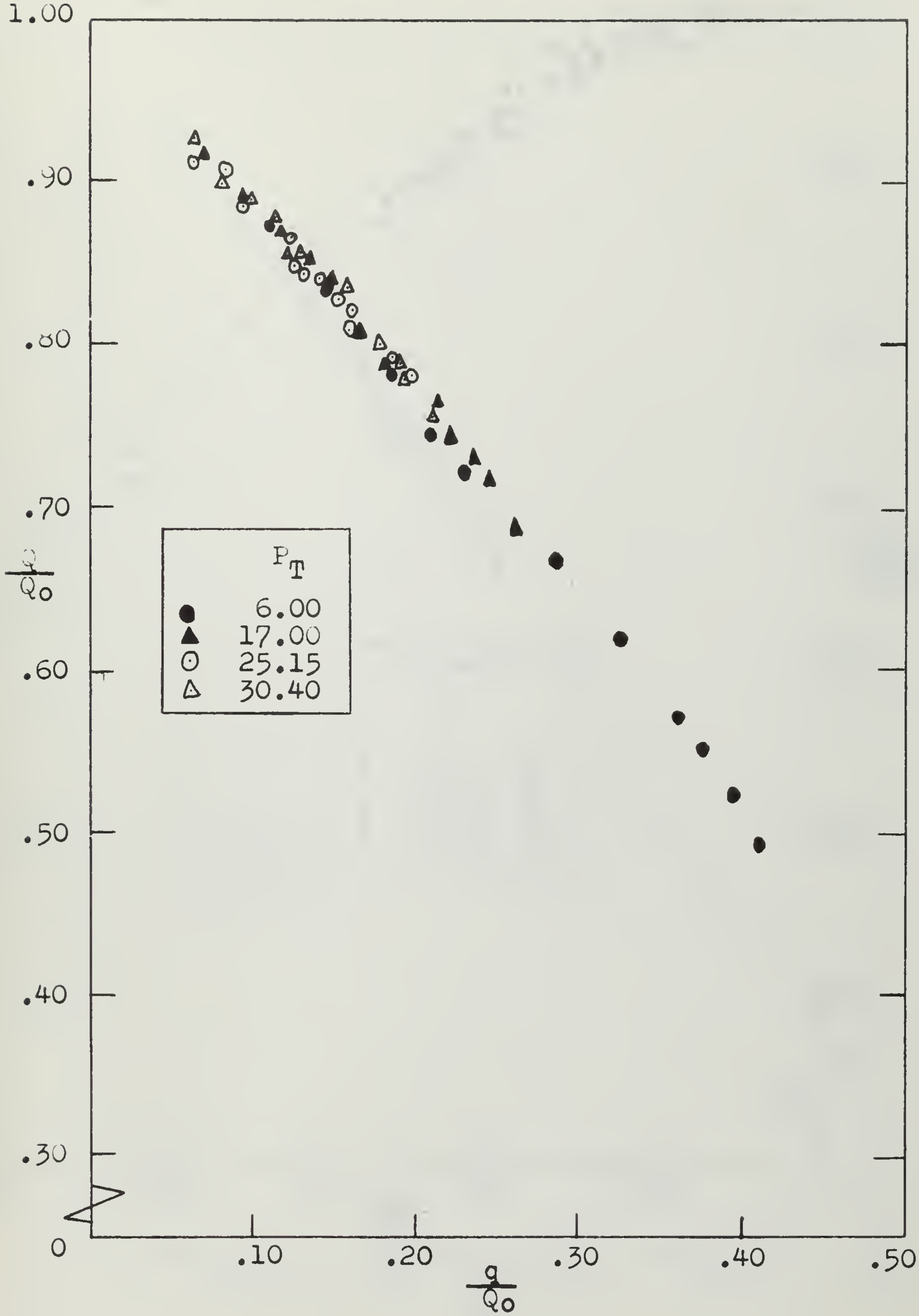


FIG. 8 PRIMARY-vs-SECONDARY FLOW RATES FOR A SHARP-EDGED ORIFICE (INJECTION ANGLE: 100 deg.)

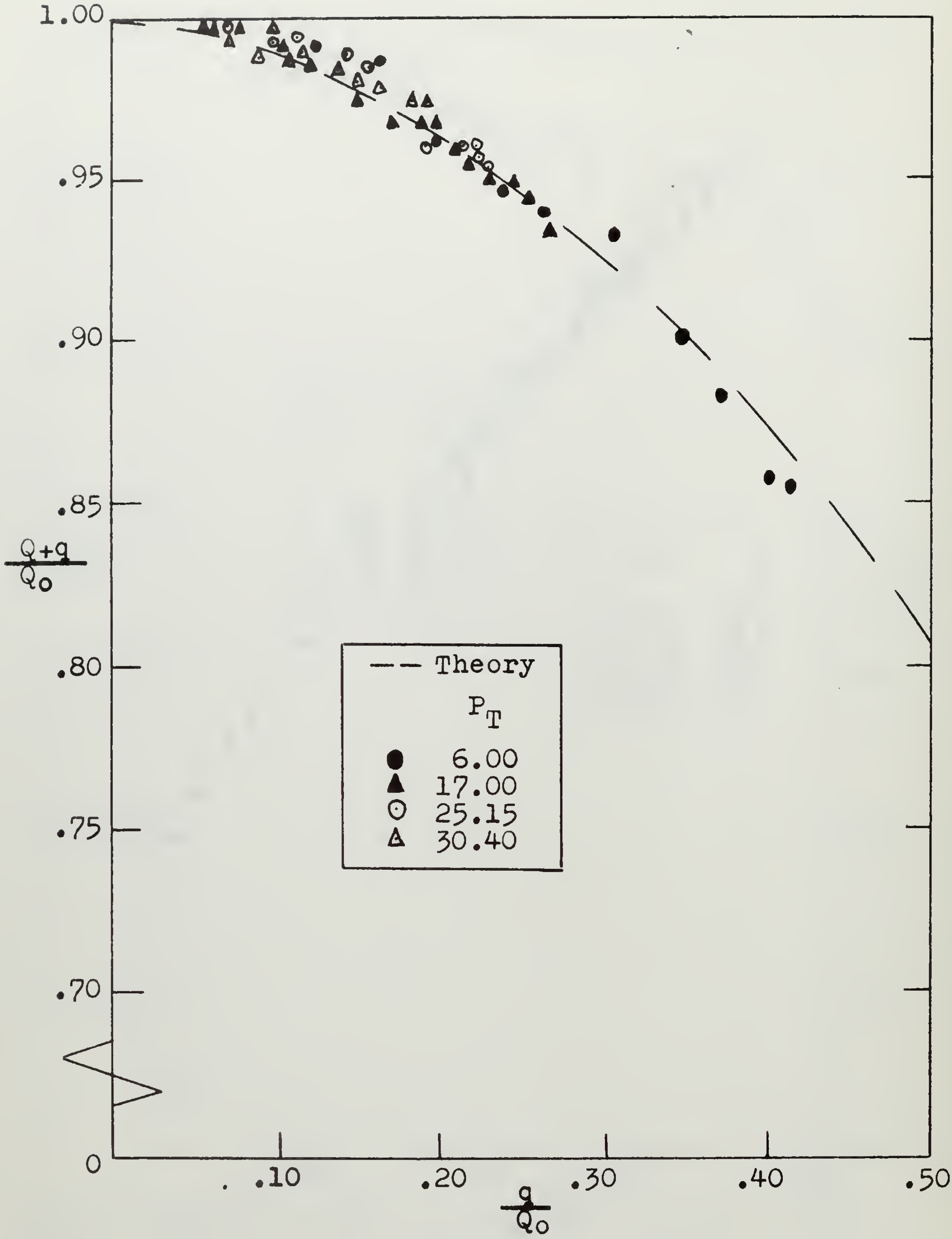


FIG. 9 EXPERIMENTAL THROTTLING DATA FOR A SHARP-EDGED ORIFICE
(INJECTION ANGLE: 110 deg.)

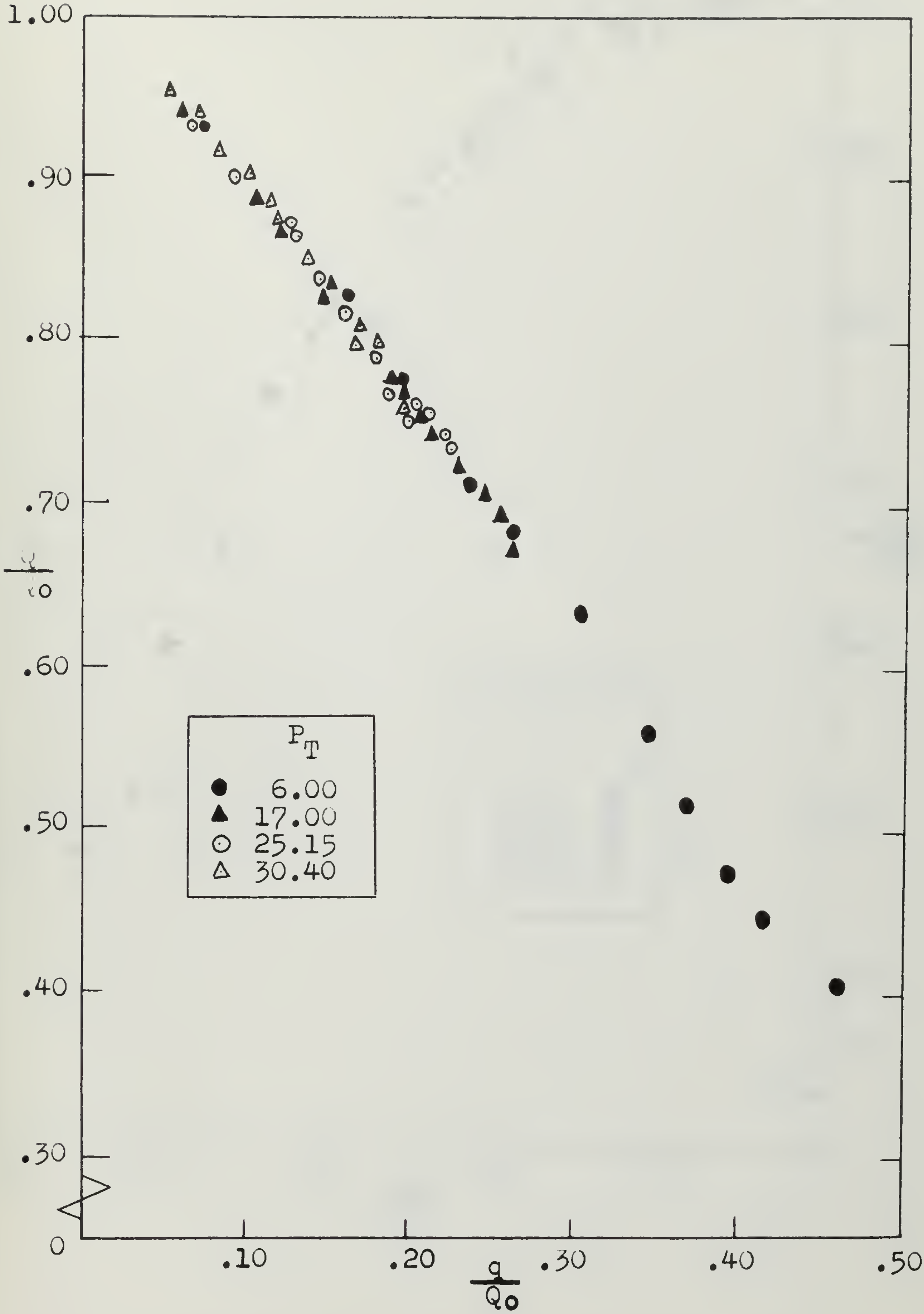


FIG. 10 PRIMARY-vs-SECONDARY FLOW RATES
FOR A SHARP-EDGED ORIFICE
(INJECTION ANGLE: 110 deg.)

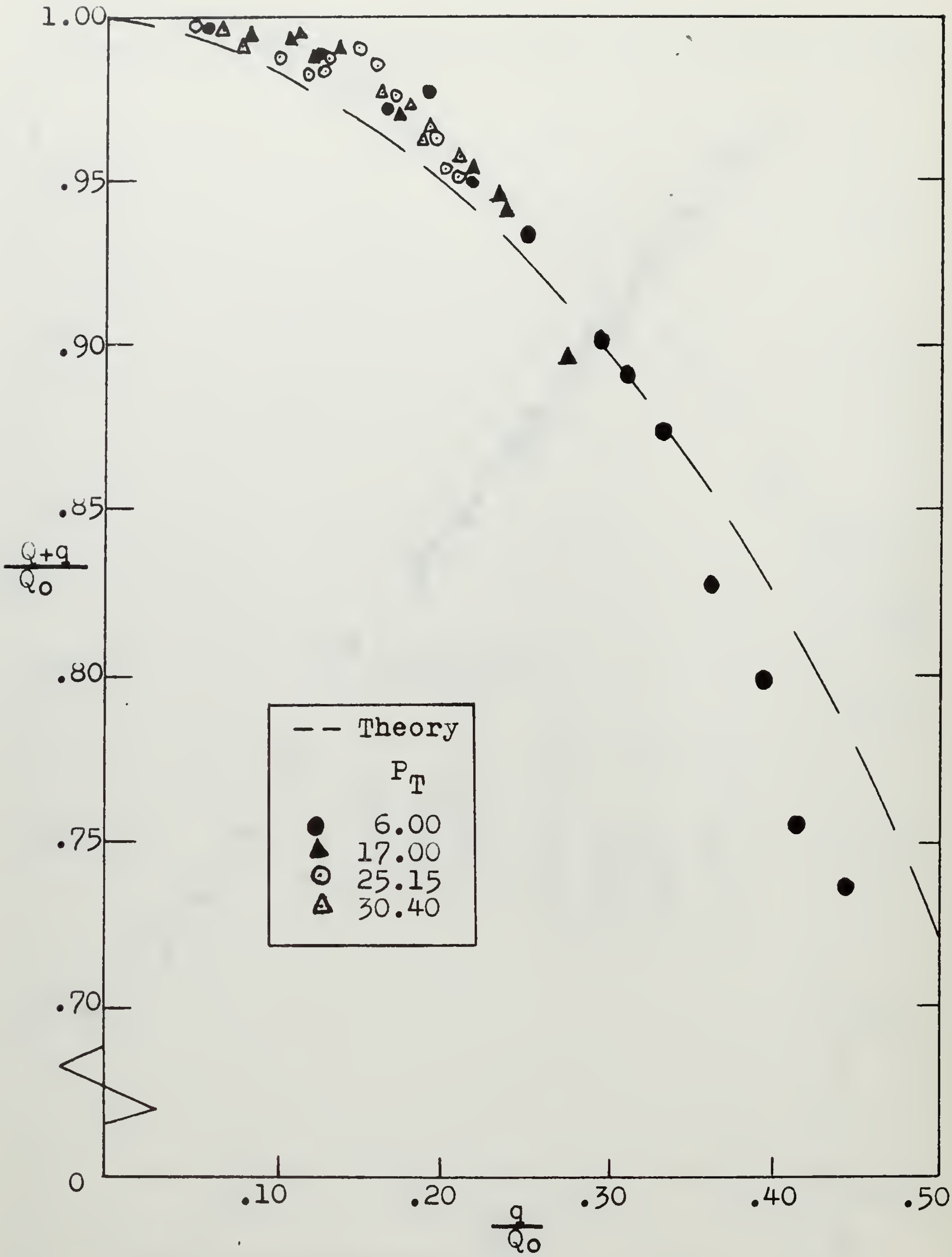


FIG. 11 EXPERIMENTAL THROTTLING DATA FOR A SHARP-EDGED ORIFICE
(INJECTION ANGLE: 120 deg.)

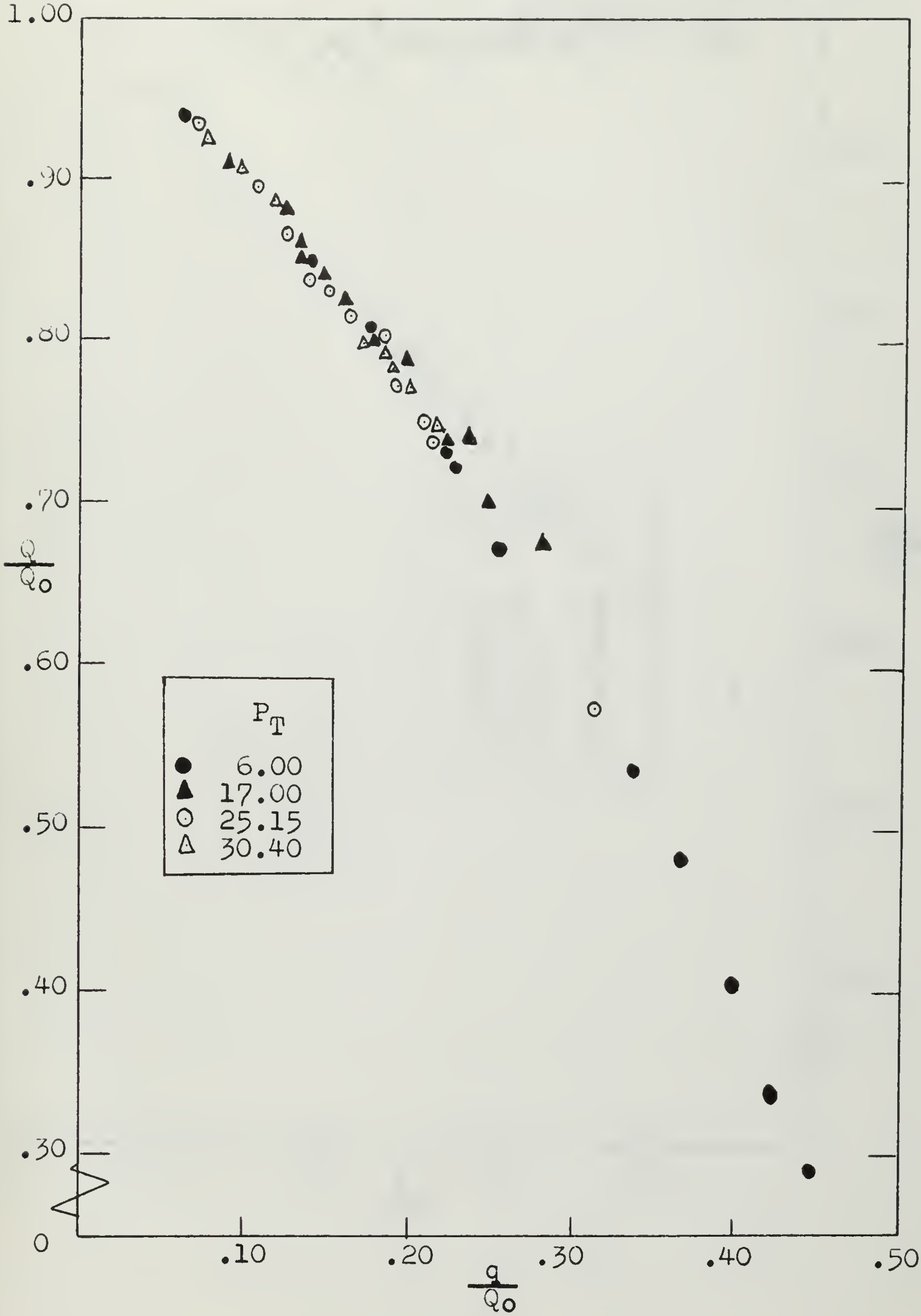


FIG. 12 PRIMARY-vs-SECONDARY FLOW RATES
FOR A SHARP-EDGED ORIFICE
(INJECTION ANGLE: 120 deg.)

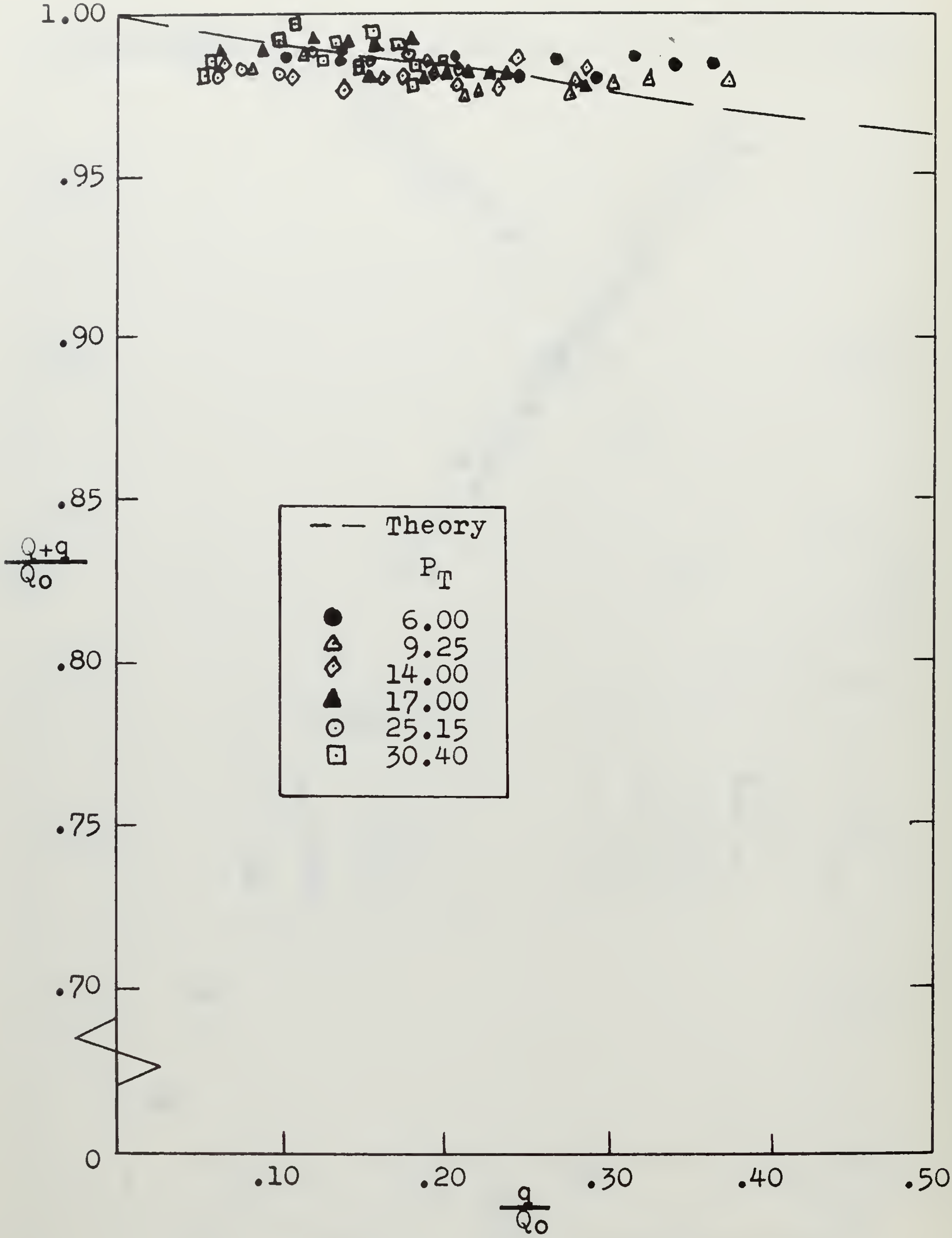


FIG. 13 EXPERIMENTAL THROTTLING DATA FOR A NOZZLE
(INJECTION ANGLE: 90 deg.)

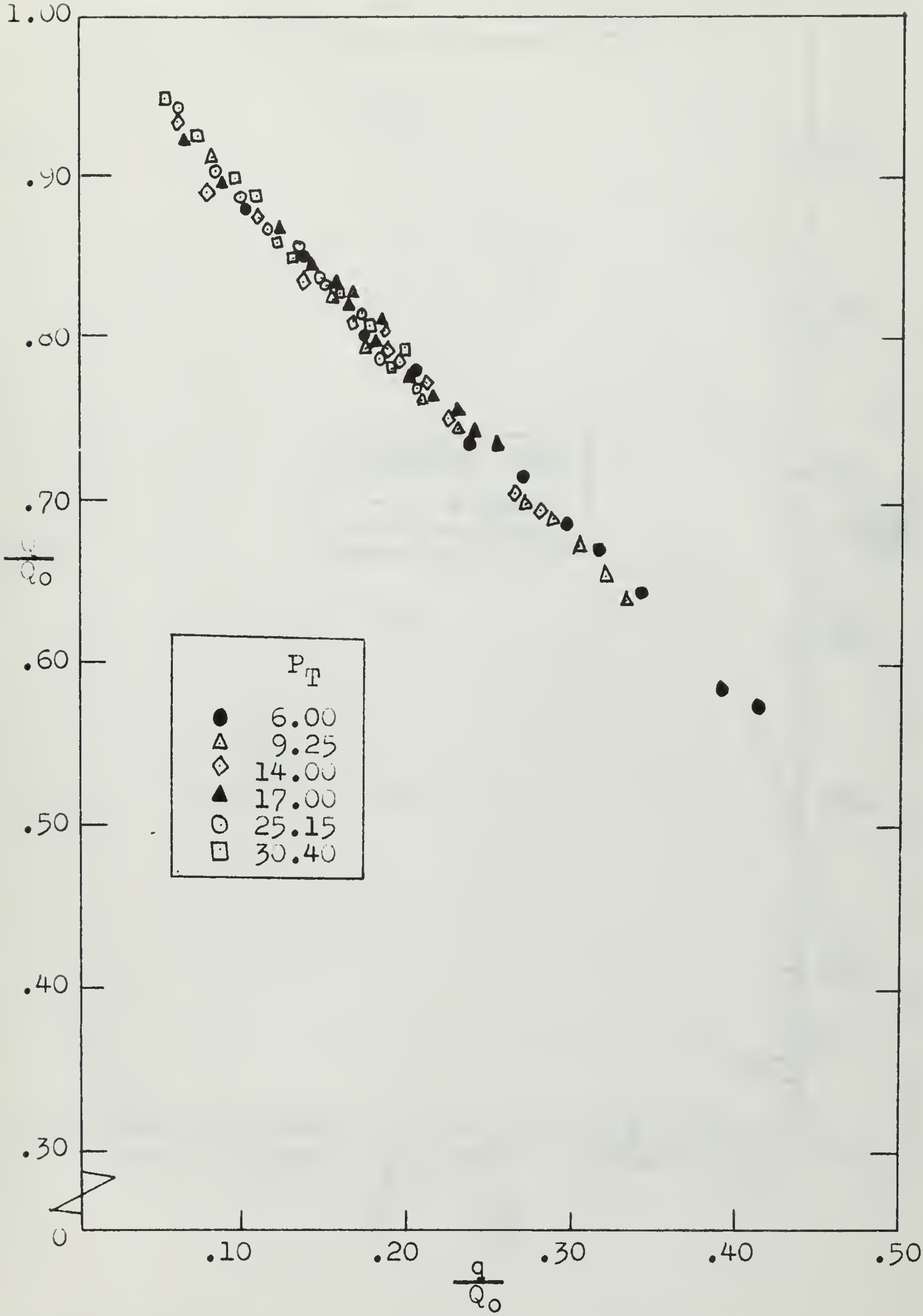


FIG. 14 PRIMARY-vs-SECONDARY FLOW RATES
FOR A NOZZLE
(INJECTION ANGLE: 90 deg.)

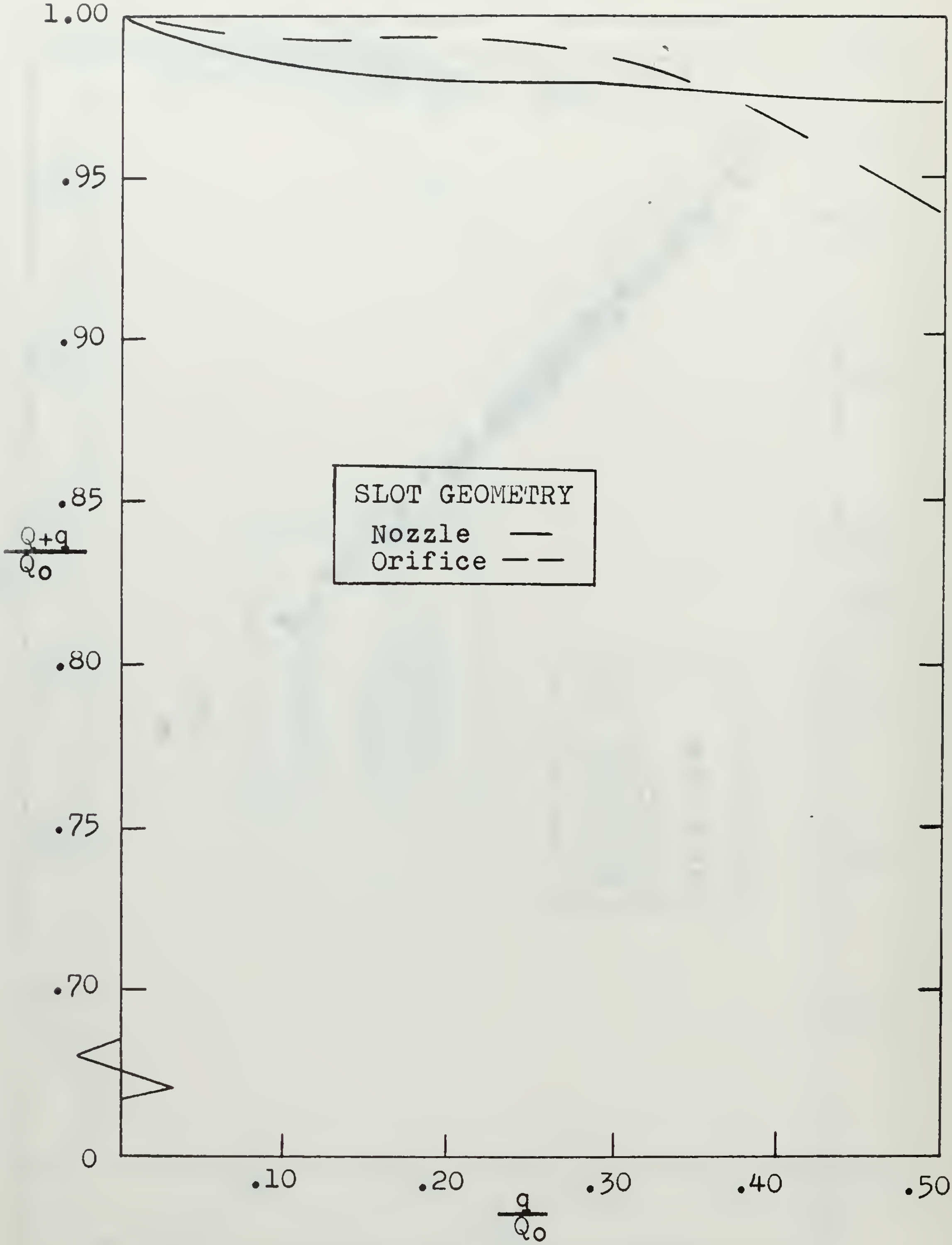


FIG. 15 COMPARATIVE PLOT OF THROTTLING DATA
FOR VARIOUS INLET GEOMETRIES

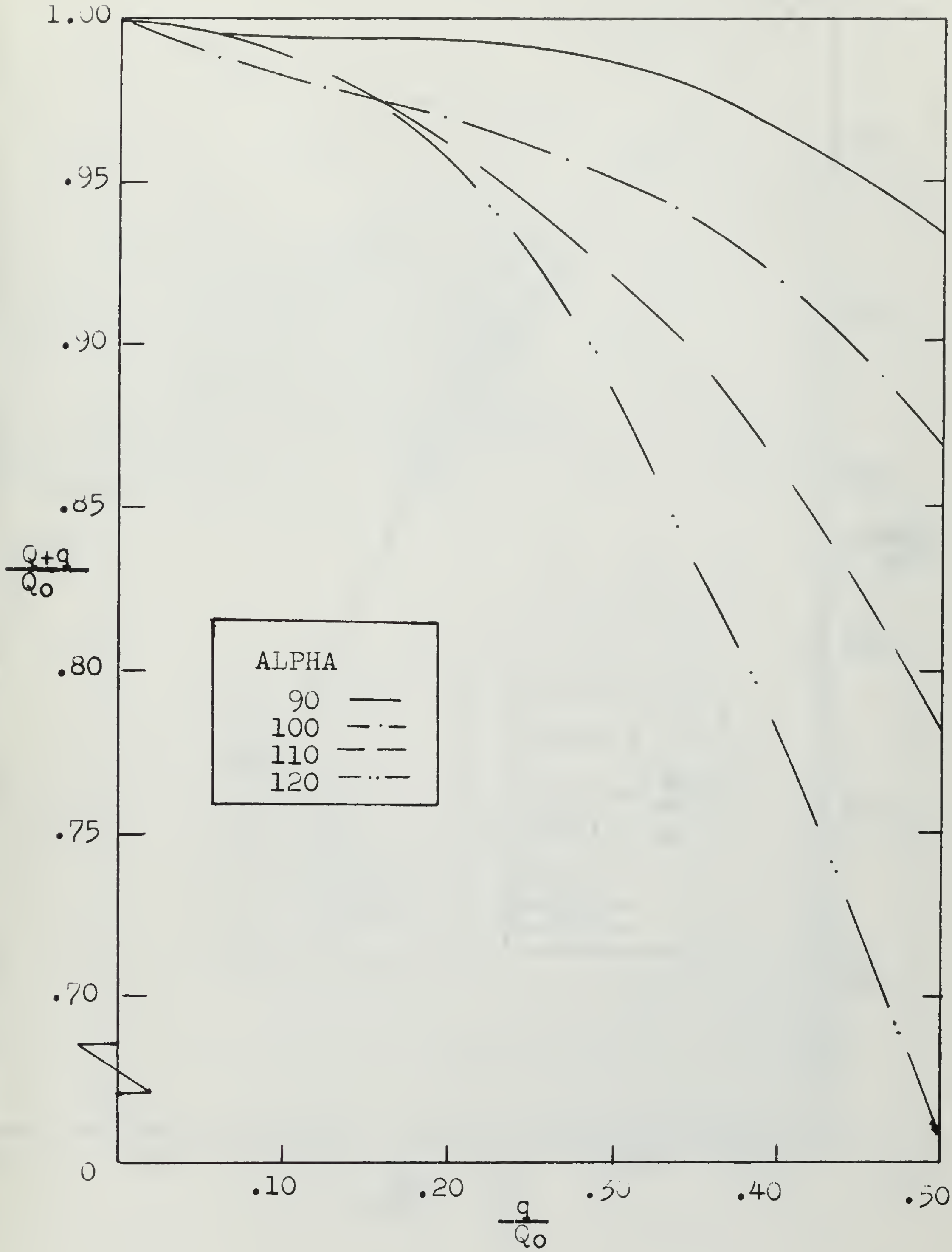


FIG. 16 COMPARATIVE PLOT OF THROTTLING DATA FOR VARIOUS ANGLES OF INJECTION

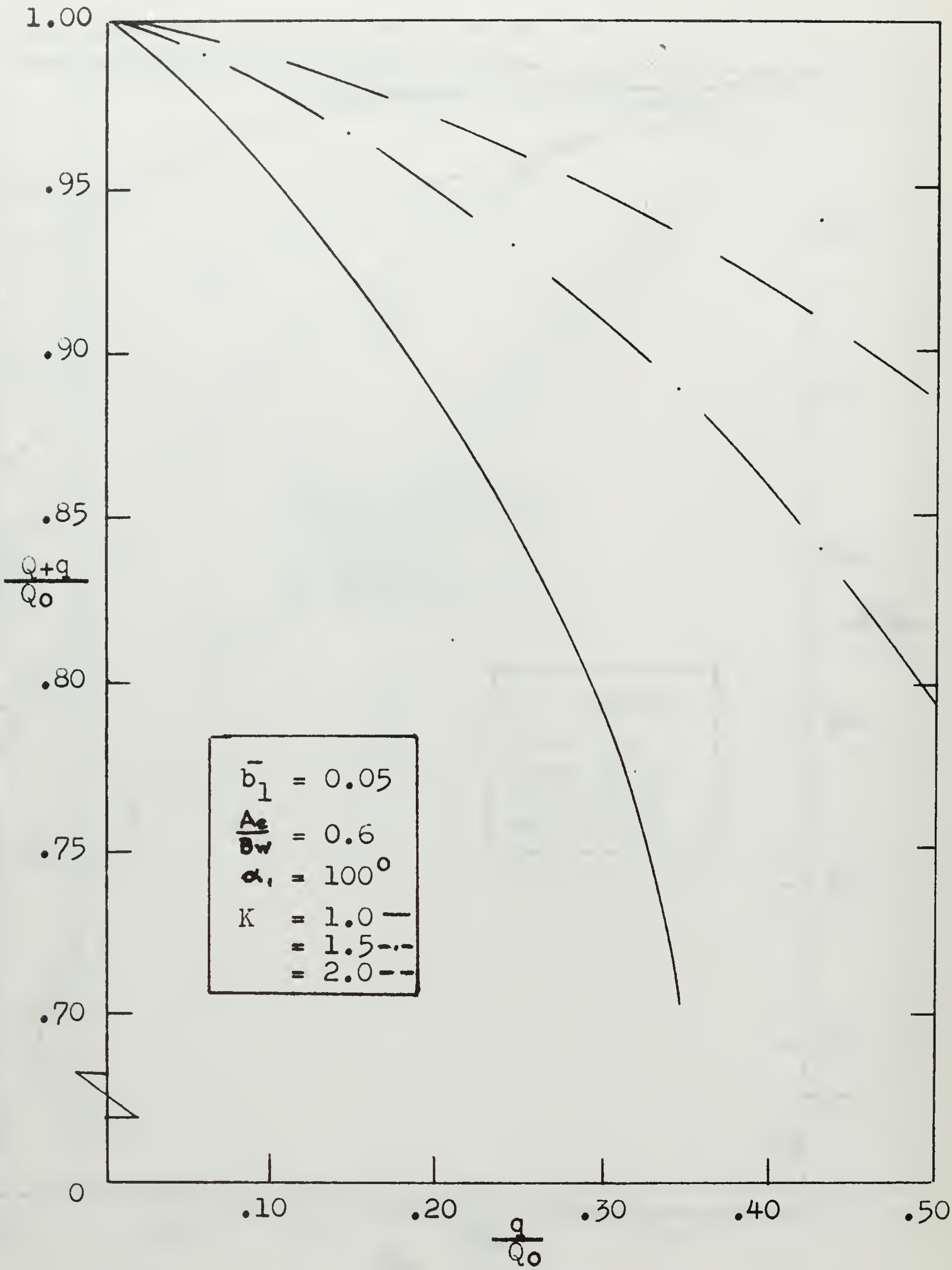


FIG. 17 MIXING HYPOTHESIS THROTTLING DATA
(PARAMETRIC IN K)

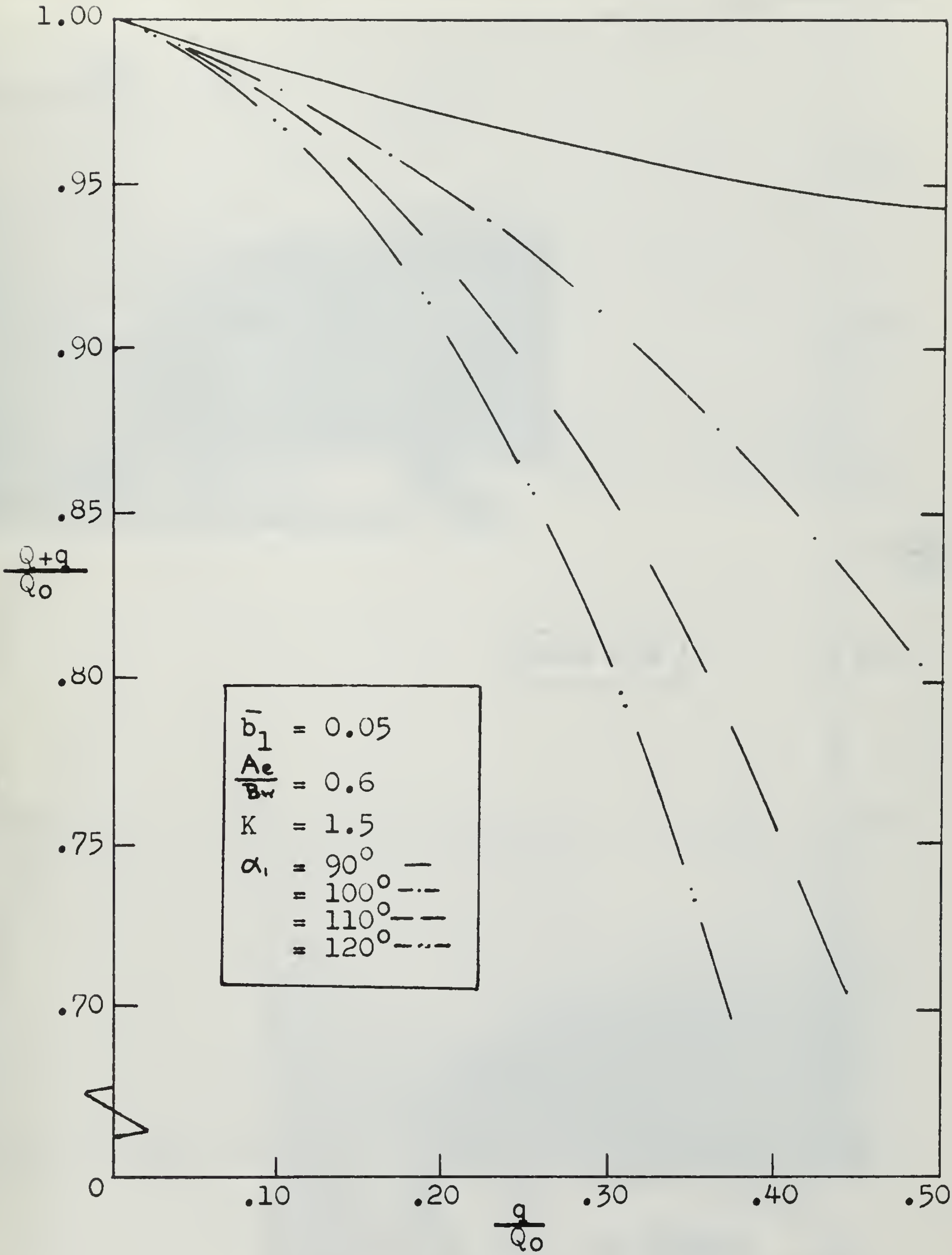


FIG. 18 MIXING HYPOTHESIS THROTTLING DATA
(PARAMETRIC IN α_1)

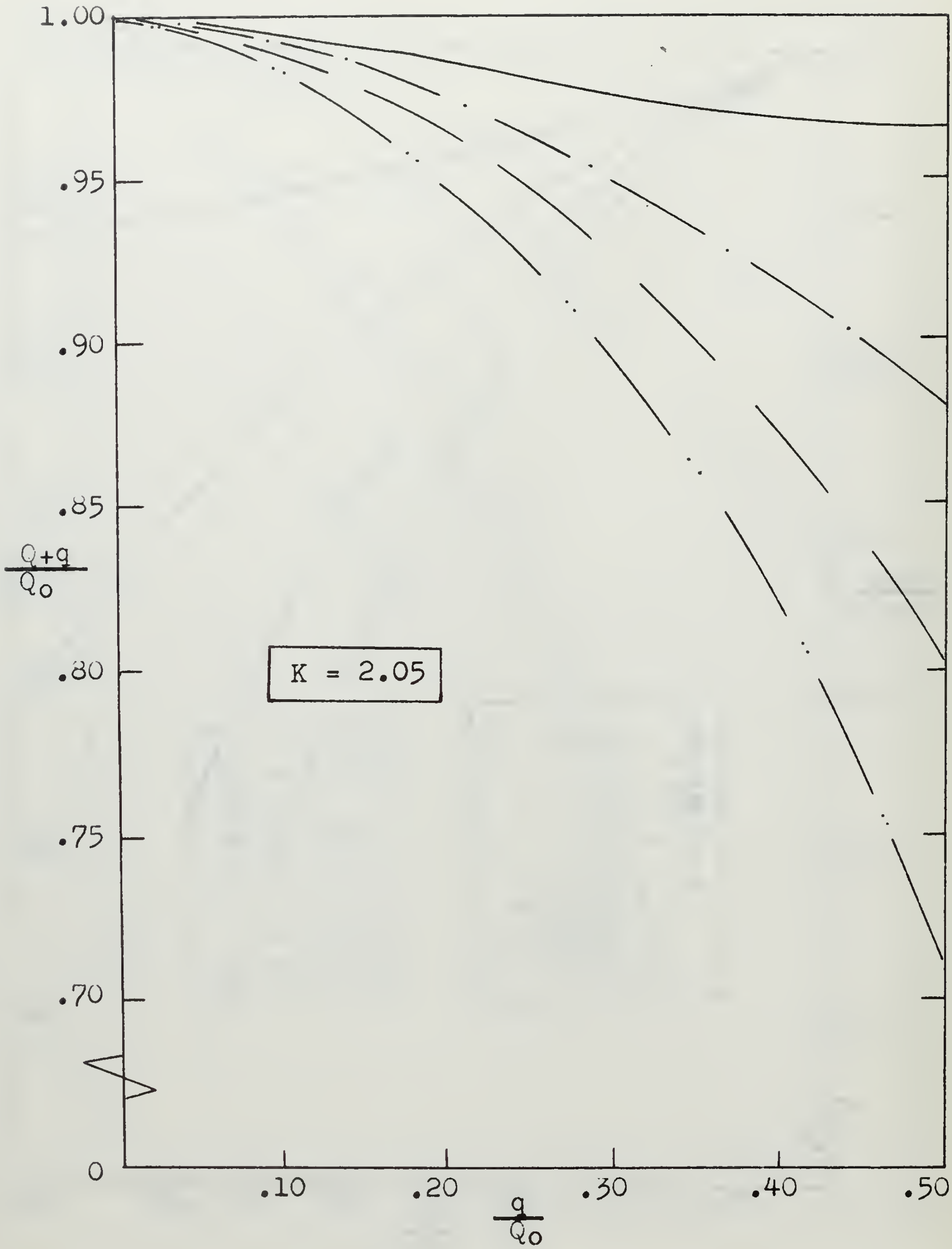


FIG. 19 MIXING HYPOTHESIS THROTTLING DATA
FIT TO EXPERIMENTAL RESULTS

(e)

(f)

FIG. 20 [illegible] VISUALIZATION
[illegible]

Fig. 11	in				α_1
(a)	[illegible]	[illegible]	[illegible]	.1[illegible]	[illegible]
(b)	[illegible]	[illegible]	[illegible]	[illegible]	110 [illegible]
(c)	1[illegible]	[illegible]	[illegible]	.1[illegible]	[illegible]
(d)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
(e)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
(f)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
(g)	[illegible]	[illegible]	[illegible]	.1[illegible]	[illegible]

( ): orifice
( ): nozzle

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13. ABSTRACT

The effect of injecting an incompressible (water) jet into a crossing mainstream water flow is investigated experimentally. The results are presented in terms of the reduction in mainstream flow rate (throttling) as a function of jet flow rate and angle of injection. The data are compared with a control volume analysis in which the two streams are assumed to mix prior to exiting the control volume.

Although the jet proved less effective than predicted as a throttling device, qualitative trends were verified. Changing the injection angle from 90° to 120° improved throttling by 25%. Smoothing the orifice to a nozzle increased throttling, but not as drastically as a 10° angle change. System refinement and a greater variation of jet parameters are necessary, however, before conclusions can be made as to the value of incompressible throttling.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Jet Throttling						
Incompressible Flow						